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Perceptual Issues in the Use of Head-Mounted Visual Displays

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Perceptual Issues in the Use of Head-Mounted Visual Displays

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Objective: We provide a review and analysis of much of the published literature on visual perception issues that impact the design and use of head-mounted displays (HMDs). **Background:** Unlike the previous literature on HMDs, this review draws heavily from the basic vision literature in order to help provide insight for future design solutions for HMDs. **Method:** Included in this review are articles and books found cited in other works as well as articles and books obtained from an Internet search. **Results:** Issues discussed include the effect of brightness and contrast on depth of field, dark focus, dark vergence, and perceptual constancy; the effect of accommodation-vergence synergy on perceptual constancy, eyestrain, and discomfort; the relationship of field of view to the functioning of different visual pathways and the types of visual-motor tasks mediated by them; the relationship of binocular input to visual suppression; and the importance of head movements, head tracking, and display update lag. **Conclusion:** This paper offers a set of recommendations for the design and use of HMDs. **Application:** Consideration of the basic vision literature will provide insight for future design solutions for HMDs.

INTRODUCTION

One important technological advance in recent years has been the development of wearable head-mounted visual displays (HMDs) for military and commercial applications (e.g., Frey & Page, 2001; Licina, Rash, Mora, & Ledford, 1999). An HMD presents symbolic or pictorial information to the eyes of a user by way of one or two miniature visual displays, such as an aiming reticle or full-color imagery (Havig, Grigsby, Heft, LaCreta, & Post, 2001), mounted on the head via a helmet or other kind of arrangement. If implemented properly, HMDs can offer advantages over traditional displays, such as increased situational awareness and ease of mobility (Velger, 1998). Thus, HMDs are increasingly being considered for use in a wide variety of applications, including surgery and other medical applications, remote vehicle operation, flight simulation, and automobile racing (Melzer & Moffitt, 1997; Velger, 1998).

Despite the potential advantages of HMDs, their development through the years has not been uniform (Ruston, Mon-Williams, & Wann, 1994; Sheedy & Bergstrom, 2002). Although Peli (1998) noted that visual effects during the use of an HMD were similar to those of a desktop display, Keller and Colucci (1998) stated that HMDs have often disappointed real-world users. Although HMDs have been used successfully in certain applications, their use in other applications has been troublesome (Velger, 1998). This is attributable, in part, to the fact that HMDs can create significant perceptual problems not found with traditional displays (Melzer & Moffitt, 1997). For example, Wenzel, Castillo, and Baker (2002) found that aircraft maintenance workers who used an HMD for training purposes reported problems such as eyestrain, headache, nausea, and dizziness. Furthermore, Morphew, Shively, and Casey (2004) found that self-reports of nausea, disorientation, and oculomotor strain were greater with an HMD as compared with a standard computer monitor for an unmanned aerial vehicle control task. Moreover, Hakkinen (2004) reported similar problems when a monocular HMD was used during performance

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of a text-editing task. Finally, Kooi (1997) reported significantly greater eyestrain with the use of HMDs as compared with a standard computer monitor. Simulator sickness has also been reported with the use of HMDs and can be caused by a number of factors (Draper, Viirre, Furness, & Gawron, 2001; Draper, Viirre, Furness, & Parker, 1997; Ehrlich, 1997).

These problems and others arise because HMDs present an unnatural viewing situation. First consider the situation in which an observer binocularly views the world under natural viewing conditions. In this case, the image projection system is linked to the environment insofar as light is reflected off surfaces and objects and projected to the user's two eyes. The views delivered to the two eyes would be similar and carry binocular disparity (also called *binocular parallax*) information. Moreover, head movements would likely alter the pattern of retinal stimulation, as would eye movements. A similar situation would occur when an observer views a typical computer display: The location of the display is fixed in the environment, the same or similar imagery is projected to the user's two eyes, and head and eye movements would likely alter the pattern of retinal stimulation.

Now consider HMDs. They can create significant perceptual problems because the image projection system is linked to the user's head, which is unnatural. The views delivered to the two eyes can be very different in the case of monocular HMDs, in which one eye sees the HMD and the other eye views a real-world scene. The two eyes' views can be different in the case of binocular HMDs as well, because the two eyes view slightly different imagery if there exists significant optical misalignment or image distortion between the two eyes' views. Moreover, in the case of HMDs, head movements would not alter the pattern of retinal stimulation (but eye movements could) unless a computer were made to shift and update the imagery shown on the HMD each time the user's head moved.

Our goal in writing this review paper was simply to research perceptual issues relevant to the use of HMDs for flight simulation and training applications. We found some excellent books describing HMD engineering design and technology issues (e.g., Melzer & Moffitt, 1997; Velger, 1998) and a plethora of research on individual issues related to HMDs but not necessarily tied extensively to the basic visual research literature.

It is our belief that new insights for potential design solutions for HMDs are to be gained by a thorough understanding of basic visual functioning. Even when a potential solution for a given problem is not immediately obvious, knowledge about basic visual functioning should have the potential of informing the development of a solution at a later time. Therefore, we have drawn upon the basic vision research literature in an effort to understand perceptual issues that may hinder the use of HMDs in flight simulation and training applications. Consequently, our review covers basic perceptual issues that are not often extensively covered in other sources, such as perceptual constancy, accommodation-vergence synergy, visual pathway functioning, and visual suppression. Thus, this review is novel in the extent to which the basic vision literature is cited and discussed when considering potential design solutions for HMDs. Approximately one half of the articles and books covered in this review derive from the basic vision literature.

The following section covers the basic components of a generic HMD system. That section is followed by sections on five key perceptual issues associated with the use of HMDs. Finally, the last section concludes with a summary of recommendations for the use of HMDs.

A GENERIC HMD SYSTEM

Many HMD systems possess common components: a type of information to be displayed, a display device attached to the head, relay optics, a combiner if the imagery is seen as superimposed on another display screen or on the outside world, and a head-tracking system (Velger, 1998). We briefly discuss the components for a generic HMD system.

Type of Information

Different types of information can be displayed on an HMD. These types are symbology, text and graphics, and real-time imagery with movement. The type of information displayed will depend upon the particular application under consideration.

In military applications information involving vehicle status, the aiming of weapons, sensors, or a target's location transmitted from other individuals may be displayed. In commercial applications, information involving maintenance and repair may be displayed. In entertainment applications, information involving gaming, movies, or personal digital assistants (PDAs) may be displayed (Hakkinen, 2004).

Display Devices

Many types of visual displays could potentially be used in HMD applications. Miniature monochrome CRT displays have generally been used with HMDs in the past because of their high luminance output, low cost, durability, and desirable temporal characteristics. Significant disadvantages of CRT displays include their relatively high weight, large size, and high power requirements (Velger, 1998).

Liquid crystal on silicon (LCoS) displays are relatively fast and have good light output, low power consumption, low weight, small size, and relatively high resolution. One disadvantage of current LCoS displays, however, is that the LCoS pixels are illuminated for an entire video frame, which may cause motion artifacts such as blurring or double images (Lindholm, Pierce, & Scharine, 2001; Winterbottom, Geri, & Pierce, 2004). This is not a major concern in applications in which only static text or graphics is viewed. For applications involving moving imagery, however, the imagery will appear to lose definition. A new type of LCoS display, called a *ferro-electric LCoS* (FLCoS) display, could provide a solution to the pixel illumination issue (Velger, 1998).

Virtual retinal displays (VRDs) present images to the visual system by scanning the images directly onto the retina using a diode laser light source and thus eliminating the display screen. The potential advantages of such a system are increased resolution, contrast, brightness, and color quality, and decreased weight. The bright high-resolution image source can be located off-helmet and its image presented to the helmet and pilot via fiber-optic image guides (Velger, 1998, pp. 109). One disadvantage of this display device for HMD applications is the small eyebox. Slippage of the helmet, or large amplitude eye movements, may cause portions of the image to disappear from view.

Digital light-processing (DLP) displays, or digital micromirror displays, operate using tiny addressable micromirrors that pivot between two orientations to reflect light out through the lens to the observer or reflect it into an absorptive material. Because the micromirrors can be switched at a high speed, such displays have the potential for presenting good quality motion. However, this potential may be undercut by the fact that current DLP displays, like the LCoS displays, are designed to illuminate each pixel for an entire video frame.

Generally, the display device is driven by one or more imaging systems, such as a digital camera or sensor attached to a moving vehicle, or an image generator (e.g., a computer providing video output). HMDs used for entertainment purposes may be driven by a DVD player, VCR, computers equipped with video output, or a PDA.

Optics

HMDs use several types of optical elements, which serve to magnify and deliver images to the eye or eyes of the user (e.g., Rash, Kalich, & van de Pol, 2002). These include diffraction optics and holographic optical elements (Velger, 1998, pp. 115–129; Wood, 1992). The different types of optical designs result in varying trade-offs in weight, image quality, field of view, and light transmittance.

Briefly, the optical elements of an HMD, together with associated hardware, can be arranged to create one of three types of HMD (Davis, 1997): a monocular HMD, wherein imagery is presented to one eye of the user while the other eye views the real world (the eye that receives the HMD imagery may also view the real world); a biocular HMD, wherein the same imagery is presented to both eyes of the user (P. J. Rogers & Freeman, 1992); or a binocular HMD, wherein imagery with binocular disparity is presented to the two eyes of the user (Klymenko, Verona, Martin, & Beasley, 1994a, 1994b).

According to Tsou and Shenker (2000), a given HMD system can be closed or occluded in that a direct view of the outside world is not possible because it is blocked or the lighting is too dark to see; the user sees only the HMD imagery. Alternatively, an HMD system can be open or semi-transparent, allowing a direct view of the outside world, and the user views the HMD imagery as superimposed upon the outside world.

Head Tracking

Some HMD systems employ conformal imagery. *Conformal imagery* refers to world-stabilized imagery that conforms to the outside world and is aligned with local geography (Velger, 1998). To create world-stabilized imagery, the imagery has to change with head position in order to simulate the shift in scene that would naturally occur with changes in head position when viewing the real world. To do so, head position has to be measured and tracked. Conformal imagery is difficult to implement because it is difficult to accurately measure head position and quickly update the imagery within a brief period (Velger, 1998).

Head trackers typically measure six degrees of freedom of head position: three angular orientations of roll, pitch, and yaw and three linear positions of *x, y,* and *z* (Velger, 1998, pp. 78, 143). Measurement of three degrees of freedom is sufficient for applications that do not require exact positioning of imagery relative to head movement. However, this type of system may not measure head roll – cocking the head slightly to the left or right, for example.

Head trackers can be electromagnetic, electro-optical, or ultrasonic. There are also inertial head trackers with mounted miniature gyroscopes that can measure high rates of head rotation (Meyer, Applewhite & Biocca, 1992; Velger, 1998). Each type of head tracker presents problems. For example, the electromagnetic trackers are affected by nearby metal objects and electromagnetic radiation (e.g., Ferrin, 1991), the electro-optical trackers require a direct line of sight and large field of view, and the ultrasonic trackers can be contaminated by external acoustic noise (Velger, 1998, pp. 80, 165).

Anderson, Vrana, Riegler, and Martin (2002) evaluated several types of head-tracking systems for use with night vision training. Inertial head trackers were recommended for enclosed areas where the placement of additional sensors is not possible. Optical head trackers were recommended for conditions in which no instruments, switches, or visual displays are located above the observer's head. Magnetic trackers were recommended for small operating spaces. (Note that magnetic and optical head trackers may have an advantage over inertial trackers because they provide for the measurement of heading, pitch, and roll as well as of *x, y,* and *z* coordinates.)

According to Velger (1998, pp. 144–145), the following ranges of head movements should be measurable with any given head tracking system: 180° for angular azimuth, 130° for elevation, and 120° for roll, with an accuracy of about 1 to 2 milliradians (mrad) on boresight and about 2 to 6 mrad at a 10° eccentricity, and linear displacements of 450 mm in the vertical axis, 400 mm in the horizontal axis, and 540 mm in the fore-aft axis.

In summary, there are many types of HMDs, depending upon the type of information displayed, the type of display employed, the type of imaging system employed, the type of optical arrangement used, and the type of head tracker used. The HMD system can be monocular, biocular, or binocular, and the optical arrangement can be either closed or semitransparent.

Now that we have covered the basic components of a generic HMD system, we turn to the discussion of several key perceptual issues that are relevant to the design and use of HMDs.

BRIGHTNESS AND CONTRAST

Brightness and contrast are important considerations when using HMDs insofar as the imagery should be clearly visible when one is wearing the HMD. Interestingly, failure to provide imagery that is bright and of high contrast has perceptual consequences other than just poor visibility. These perceptual consequences will be discussed.

Depth of Field

When an HMD is worn while one is viewing a real out-the-window (OTW) scene, such as with helmet-mounted sights, both the HMD imagery and the OTW view must be clearly visible at the same time. For this to occur, the HMD imagery and any objects in the OTW view must be within the user's depth of field. *Depth of field* refers to the range of distances in object space within which stimuli appear in sharp focus. One factor that determines the user's depth of field is the focal distance at which the HMD is set. Establishing that the HMD imagery and the objects in the OTW view are all within the user's depth of field should not be a significant problem because the HMD optics are typically collimated for this application. That is, the focal distance of the HMD is set to near optical infinity so that both the HMD imagery and the OTW scene are in focus simultaneously. However, when one wears an HMD while viewing another synthetic vision display, such as the visual display of a flight simulator, both HMD imagery and the simulator imagery must be clearly visible at the same time. For this to occur, both the HMD and simulator imagery must be within the user's depth of field.

For the dome type of simulator displays, the focal distance of the HMD would be set to a value that equals the radius of the dome. However, for multifaceted simulator displays, when the corner of the background display is viewed from the observer's position (i.e., off-axis viewing), the viewing distance would be greater than when the display is viewed in the straight-ahead position. This raises the question of whether the focal distance of the HMD should be set to a value that matches the distance of the straight-ahead view, to a value that matches the distance of the off-axis view, or to an intermediate value.

This issue could be tested by using an acuity measure and presenting targets on an HMD for a duration shorter than the latency of the accommodative response, which can range from about 370 ms to 1 s or more (Campbell & Westheimer, 1960). This approach could be used to measure depth of field for a given application and determine whether the focal distances of two different displays are within the user's depth of field.

Brightness and contrast of the HMD symbology can affect the user's depth of field, as can pupil size and level of resolution. Generally, increases in luminance level produce a smaller pupil, which leads to a greater depth of field. For example, Ogle and Schwartz (1959) report that for each millimeter of increase in pupil size (ranging from 2.5 to 8.0 mm), depth of focus decreased by 0.12 diopters. (*Depth of focus* refers to the range of distances in image space within which an image appears in sharp focus.) Conversely, a greater degree of resolution will lead to a smaller depth of field (Campbell, 1957; Ogle & Schwartz, 1959). Ogle and Schwartz (1959) showed that for each step of increase in target resolution, the total depth of focus decreased by 0.35 diopters. Thus, one cannot easily specify a given difference in focal distances that individuals can tolerate; a number of factors enter into the determination of the depth of field. Thus, it is important to take into account all relevant factors when designing an HMD system.

Dark Focus and Dark Vergence

When considering the focal distance of the HMD, one needs to take into account the dark focus of human observers. *Dark focus* refers to the tendency of accommodation to drift toward a resting distance of approximately 1 m from the observer, which occurs more under degraded stimulus conditions (Hennessy, Iida, Shina & Leibowitz, 1976; Leibowitz & Owens, 1975a, 1975b). For example, Leibowitz and Owens (1975b) measured accommodation while a building was viewed at a distance of 200 m under bright daylight conditions and when the same scene was viewed through neutral density filters, which lowered luminance level. These authors found that whereas the accommodative response was driven mainly by the stimulus (building) under bright viewing conditions, the accommodative response became a compromise between the response driven by the stimulus and the dark focus value when luminance level was reduced by 1.95 log units. (On the assumption that the luminance level of a bright outdoor scene can be on the order of 34,262.6 cd/m^2 [Velger, 1998, p. 90], this would make the luminance level roughly 342.6 cd/m^2.) The accommodative response was close to being the dark focus value when luminance level was reduced by 4.2 log units (an estimated luminance level of roughly 3.4 cd/m^2). However, there are large individual differences in the actual dark focus value when measured across individuals (Leibowitz & Owens, 1975a), and it likely would not be possible to predict in advance what any given individual's dark focus value would be.

In general, HMD focal distances that are increasingly farther from an individual's dark focus value will tend to produce errors of accommodation and poor visual resolution, especially under conditions of low illumination (e.g., below about 6.9 cd/m^2; see Johnson, 1976). Owens (1979) showed that the accommodative response will be biased toward the distance that is closer to the user's dark focus value; the stimulus near the dark focus value will require less accommodative effort (for a contrasting view, see Gleason & Kenyon, 1997). This may have significance for situations in which two stimuli with different focal distances are optically superimposed, such as when an observer views an OTW scene through a semi-transparent HMD with a focal distance that is not close to optical infinity.

There is also an analogous phenomenon of *dark vergence,* which refers to the tendency of vergence to drift toward a resting distance of a little more than 1 m from the observer. In a study by Ivanoff (1955), convergence was close to the angle corresponding to the target distance for luminance values at and above 0.1 cd/m^2. (For typical HMD applications, this latter value would represent a very low and unrealistic luminance level.) For luminance levels below that value, convergence approached the dark vergence angle.

Perceptual Constancy

The tendency for accommodation to drift toward dark focus and vergence to drift toward dark vergence, especially under degraded stimulus conditions, may cause the size, depth, or speed of the HMD imagery to be misperceived. Such misperception would be related to misperceived distance and the concept of perceptual constancy (Patterson & Martin, 1992), as we will explain.

Stimuli can be subdivided into two categories, distal and proximal stimuli (Epstein, 1997). The term *distal stimuli* refers to the stimuli that exist out in the environment; the term *proximal stimuli* refers to the stimuli that impinge upon the eye's rods and cones. The function of the visual system is to glean information about distal stimuli from information carried by proximal stimuli, a task made difficult by the existence of changing environmental conditions. For example, consider the perception of size. When an observer moves closer to an object, retinal image size increases, and in order for the observer to correctly perceive that the object's actual size (distal stimulus) did not vary (which is called *size constancy*), the visual system likely combines information about visual angle and viewing distance (Foley, Ribeiro-Filho, & Da Silva, 2004), which involve proximal stimuli.

Similarly, consider the perception of stereoscopic depth, which is the perception of depth based upon binocular disparity. When an observer moves closer to a set of objects that vary in depth, binocular disparity increases, and in order for an observer to correctly perceive that the actual depth relations among the stimuli (distal stimuli) did not vary (which is called *depth constancy*), the visual system likely combines information about binocular disparity and viewing distance (Howard & Rogers, 1995, 2002; Ono & Comerford, 1977; Patterson, Moe, & Hewitt, 1992; Ritter, 1977), which involve proximal stimuli.

An analogous phenomenon may occur with perceived speed. When an observer moves closer to a laterally moving object, the speed of the object's retinal image increases, and in order for the observer to correctly perceive that the actual speed of the object did not change (which is called *speed constancy*), the visual system may combine information about retinal speed and viewing distance. In this case, however, the existence of speed constancy is controversial. Some authors (Pierce & Geri, 1997; Wallach, 1939; Zohary & Sittig, 1993) have found evidence for speed constancy, at least under some conditions, but other authors (McKee & Welch, 1989) have not.

In the three types of constancies mentioned previously, size, depth, and speed, the visual system is said to scale retinal size, binocular disparity, or retinal speed, respectively, in accordance with viewing distance information, a process called *distance scaling*. One issue in the literature regarding perceptual constancy concerns the kind of visual cues that may be used for distance scaling. In particular, there is some evidence that proprioception from ocular vergence may provide information for distance scaling, at least for short viewing distances such as those encountered with HMDs. For example, von Hofsten (1976) investigated perceived distance while observers viewed a target through a polarization stereoscope and found that perceived distance was determined by relative differences in convergence angle, not by absolute convergence angle. Owens and Leibowitz (1976) investigated the relationship among dark focus, dark vergence, and the perceived distance of a light point presented in the dark. The results showed that perceived distance was correlated with dark vergence but not with dark focus. These authors suggested that vergence may be a major cue to distance perception. A follow-up study by Owens and Leibowitz (1980) revealed a similar correlation between perceived distance and vergence using an adaptation paradigm. Wetzel, Pierce, and Geri (1996) also reported a strong relationship between vergence and perceived size when viewing objects on near (0.61 or 0.95 m) and far (8 m) real-image displays.

Thus HMDs that cause vergence to drift toward a dark vergence level, such as low-contrast or dim displays, may cause distance to be misperceived. This, in turn, may cause the size, depth, or speed of HMD imagery to be misperceived owing to inappropriate distance scaling (Patterson & Martin, 1992). Moreover, with respect to the use of monocular HMDs, the vergence system becomes open loop because only one eye sees the HMD imagery. Under such conditions, it may be that perceived distance is affected in complex ways. Ellis, Bucher, and Menges (1995) reported that errors of judged depth of virtual objects are associated with variation in binocular vergence.

Moreover, there is some evidence that proprioception from accommodation may provide information for distance scaling and that misaccommodation may affect perceived distance. Edgar, Pope, and Craig (1993) reported that many people misaccommodate when viewing virtual displays superimposed upon a real scene and that such misaccommodation can lead to misperceived distance and size. (Note, however, that Owens & Leibowitz [1976, 1980] found no relation between accommodation and perceived distance.) Peli (1990) also noted that the perceived size of imagery on a monocular, occluding HMD appears to change depending on the distance of the surface to which the opposite eye is accommodated. HMDs that cause accommodation to drift toward a dark focus level, such as low-contrast or dim displays, may cause perceived distance to be misperceived. This, in turn, may cause the size, depth, or speed of HMD imagery to be misperceived owing to inappropriate distance scaling (Patterson & Martin, 1992).

Recommendations

Perceptual research reveals that there are perceptual consequences related to low contrast and brightness in HMDs. Specifically, depth of field, dark focus and dark vergence, and perceptual constancy can be affected by low contrast and brightness. With respect to perceptual constancy, it involves a cue integration process that could affect the perceived size, depth, and/or distance of objects presented within the HMD if any of the relevant cues are misregistered by the visual system. Moreover, dark focus and dark vergence can affect HMD visibility as well as produce a misregistration of oculomotor cues, which may affect perceptual constancy. Thus, HMD brightness and contrast should be sufficient so as to minimize the tendency for accommodation to drift toward dark focus, and minimize the tendency for vergence to drift toward dark vergence, and at the same time produce a relatively large depth of focus so that HMD images appear sharp and in focus while the user is viewing the outside world or another display.

With respect to a recommended minimum luminance level, vergence appears to be valid down to a level of 0.1 cd/m^2 (Ivanoff, 1955). Accommodation, however, appears to be valid down to a level of somewhere between 6.9 cd/m^2 and 342.6 cd/m^2 (Johnson, 1976; Leibowitz & Owens, 1975b). Thus, the accommodation response seems to set the lower limit on the usable luminance level of HMDs. With respect to a recommended minimum contrast level, a Michelson contrast of at least .10 is desirable (Velger, 1998, pp. 70–71). For example, when imagery presented on an HMD is seen against the outside world under daylight conditions, the luminance of the image source should be approximately 27,410.1 cd/m^2 (Velger, 1998, p. 90), which would make the Michelson contrast of the symbology be about .10, or make the contrast ratio be about 1.2, in which *contrast* is defined as the ratio of the luminance of the virtual image to the luminance of the outside world transmitted through a combiner (Velger, 1998, pp. 70–71). However, the Video Electronics Standards Association flat panel display measurements standard, version 2.0, 2001, recommends a minimum contrast of .25 to maintain visibility of imagery.

ACCOMMODATION-VERGENCE SYNERGY

When one views an HMD, the stimulus to accommodation would be the imagery presented on the surface of the HMD. However, if the user changes his or her vergence angle to view a target appearing in a virtual 3-D scene presented on the HMD, the vergence angle can be mismatched relative to accommodative demand (Wann, Ruston, & Mon-Williams, 1995). An analogous situation can occur when a monocular HMD is worn and the imagery is fixated. In this case, the accommodative stimulus is the HMD imagery but vergence becomes open loop because the imagery is presented to only one eye.

The existence of an accommodation-vergence mismatch can create several problems for the HMD user and arise, in part, from the strong synergy and coupling between accommodation and vergence (Toates, 1972, 1974). An accommodation-vergence mismatch can create eyestrain or visual discomfort, a frequently reported problem with HMD use (Mon-Williams, Wann, & Ruston, 1993; Ruston et al., 1994; Shibata, 2002; Velger, 1998). Moreover, an accommodation-vergence mismatch can cause the HMD imagery to become blurred because vergence would be driving accommodation to respond to a focal distance that would be different from the distance at which the stimulus for accommodation is established. Finally, an accommodation-vergence mismatch may alter the perception of distance, size, depth, or speed of objects presented on the HMD for reasons discussed previously relating to perceptual constancy. Recall that the visual system likely scales retinal size, binocular disparity, and perhaps retinal speed in accordance with viewing distance information, a process called *distance scaling*. If proprioception from ocular vergence and/or accommodation provides information about viewing distance (Edgar et al., 1993; Ellis et al., 1995; Owens & Leibowitz, 1976, 1980; von Hofsten, 1976; Wetzel et al., 1996), then an accommodation-vergence mismatch may disrupt the distance scaling operation and cause the size, depth, or speed of HMD imagery to be altered (Patterson & Martin, 1992).

Sheedy and Bergstrom (2002), who had participants perform several text-based tasks as well as a routine of head and body movements, compared five types of displays: monocular head-mounted, binocular head-mounted, hard copy, flat panel, and a small-format portable display. Performance speed on the text-based tasks with HMDs was generally comparable to performance on the other displays, but symptoms of eyestrain and blurry vision were significantly higher with the former displays. Those authors also found that motion-related symptoms with the HMDs were not significantly different from those with the other displays. Unlike many past studies, theirs found that performance and comfort on the HMDs were more similar to those with traditional displays, which was likely attributable in part to concordance of the accommodative and vergence stimuli (i.e., the tasks did not induce the observers to significantly change convergence angle).

Recommendations

An accommodation-vergence mismatch can affect the perceived size, depth, and distance of objects presented within an HMD because of the operation of perceptual constancy. Such a mismatch can also create eyestrain and discomfort. These problems will be less for tasks that do not induce the user to significantly change convergence angle; the problems will be greater when objects in a virtual scene are displayed in depth and the user is induced to change convergence angle. More research is needed to determine the exact limits of tolerance for accommodation-vergence mismatch.

FIELD OF VIEW

The field of view of an HMD is important for the obvious reason, other factors being constant, that a larger field of view will better simulate natural viewing, given that the field of view of the human visual system extends 200° horizontal by 130° vertical, with the central 120° being the area of binocular overlap (Velger, 1998, p. 50). Wide fields of view can be created with relatively large optics (which increases the weight of the system) or smaller eye relief (Velger, 1998, pp. 64–65). However, increasing field of view will decrease display resolution because the same pixels are mapped to a larger display area (Fisher, 1994).

A large field of view will produce a greater sense of immersion (Primeau, 2000) as well as provide the stimulus conditions necessary for adequate visual functioning (also see S. P. Rogers, Asbury, & Szoboszlay, 2003). Accounting for this is the fact that the visual system is anatomically subdivided into two different visual pathways, one predominately activated by stimulation in the central portion of the retina and the other activated by stimulation in the central retina and periphery. Thus, a restricted field of view may activate, or fail to activate, these two pathways in an unnatural way. In order to consider the implications of a restricted field of view, we now turn to a brief discussion of these two visual pathways.

Visual Pathways

The visual system is composed of the parvocellular and magnocellular pathways (e.g., Livingstone & Hubel, 1988; Schiller, Logothetis, & Charles, 1990). The parvocellular pathway has connections mainly from the central retina, and it projects to areas in the visual cortex that make up the ventral cortical stream. Areas in the ventral stream functionally analyze spatial pattern information. Cells in these cortical areas have a sustained or sluggish response and poor temporal acuity. Many cells in these areas respond to color information, and many cells respond to fine detail and high spatial frequency information. The ventral stream is thought to be involved in the functional analysis of spatial pattern information for the purpose of identifying objects.

The magnocellular pathway has connections from the central and peripheral retina, and it projects to areas in the visual cortex that make up the dorsal cortical stream. Areas in the dorsal stream functionally analyze optic flow information for heading control (Peuskens, Sunaert, Dupont, Van Hecke, & Orban, 2001) and biological motion (Grossman & Blake, 2001; Grossman et al., 2000), and they integrate vision with action (e.g., T'so & Roe, 1995; Van Essen & DeYoe, 1995; Yabuta, Sawatari, & Callaway, 2001). Cells in these cortical areas have a transient response and high temporal acuity. Cells in these areas do not respond to color information but do respond to coarse detail and relatively low spatial frequency information. The dorsal stream is thought to be involved in the functional analysis of motion information for the purpose of determining spatial relations and controlling heading during locomotion.

Milner and Goodale (1995) made an even greater distinction between the two pathways. They claimed that the ventral stream is involved in the representation of visual experience, whereas the dorsal stream is involved in action priming and motor control. This view implies that information gleaned from research on visual judgments and reports, which would involve ventral stream functioning, would not necessarily generalize to sensory-motor control tasks, which would entail dorsal stream functioning.

Restricted Field of View

Turning back to the issue of field of view, using an HMD with a restricted field of view would mean that stimulation would occur mainly in the central portion of the retinae of the two eyes. Although eye movements usually would be possible with an HMD, it is likely that the user would spend much of the time looking in the forward direction. This, in turn, would mean that the ventral stream, and not the dorsal stream, would be predominantly activated. Under such conditions, an observer's ability to control heading or process spatial orientation might be compromised, as might be the sense of immersion.

For example, Allison, Howard, and Zacher (1999) investigated the effect of the size of the field of view on roll vection and illusory self-tilt in a tumbling room. They found that complete 360° body rotation (tumbling) and increased speed of self-rotation were perceived by most observers under a full-field condition. For smaller fields of view, tilt or partial tumbling and slower speeds of self-rotation were perceived. When the field of view was 50°, one half of all observers reported tumbling at an intermediate speed. This suggests that a field of view of at least 50° is needed for some sense of immersion and that a larger field of view would be needed for a complete sense of immersion.

Of course, the required size of field of view for an HMD would depend upon the application under consideration. In a study involving a simulated nighttime attack, Osgood and Wells (1991) examined size of the field of view of the image from an aircraft-fixed sensor seen on a head-up display (HUD) and for a head-steered sensor seen on an HMD. With the HMD, observers acquired the targets quicker up to a field of view of 40°, beyond which performance did not significantly change. Kenyon and Kneller (1993) investigated the effect of field of view on a visual tracking task and found that near asymptotic performance was obtained with a field of view of only 40° (also see Jennings & Craig, 2000). Note that these studies involved tasks that likely depended upon activation primarily of the ventral stream.

Other studies have involved tasks that likely depended upon activation of the dorsal stream. For example, Brickner and Foyle (1990) reported that field of view affected heading control in a flight simulator, with more narrow fields of view (e.g., 25°) leading to impaired performance relative to larger fields of view (e.g., 55°). Weikhorst and Vacarro (1988) found that maneuvers performed by pilots in a flight simulator, such as the aileron and barrel roll, were performed significantly better with a very wide field of view of 300° than with a field of view of 36° or 144°. They also found that the accuracy in dropping bombs improved when the field of view was larger. In a study involving low-altitude flight, Kruk and Runnings (1989) varied field of view from 87° to

127° and found that the subjective workload of pilots was substantially higher with a limited field of view. Moreover, significant increases in maneuvering time were found for formation flying as field of view was decreased, presumably because of a lack of motion cuing and a reduced horizon reference. Finally, for a binocular HMD involving OTW viewing, a field of view greater than 50° was required for creating a sense of immersion (Clapp, 1987; Fisher 1994; Velger, 1998, p. 65).

In a study involving a large non-HMD display, Duh, Lin, Kenyon, Parker, and Furness (2001) found that observers showed greater amounts of postural disturbance with increasing field of view, up to a field of view of 180°, the largest value tested. In a related study also involving a non-HMD display, Lin, Duh, Parker, Abi-Rached, and Furness (2002) found that observers reported higher levels of simulator sickness, as well as higher levels of "presence," with increased field of view, up to a field of view of 140°. These results suggest that a large field of view is needed for creating a sense of immersion, which in turn is related to a greater potential for simulator sickness and postural instability. This is likely because a larger field of view engages more of the dorsal stream, which would be responsible for postural control and body alignment in space, and thus a greater potential is created for a mismatch between the vestibular system and the visual system.

Melzer (1998) suggested several techniques for creating HMDs with a large field of view as well as high resolution. These techniques include designing high-resolution areas of interest or implementing a partial binocular overlap design.

Recommendations

The functioning of the parvocellular and magnocellular pathways and the ventral and dorsal cortical streams determines, in part, the type of visual-motor tasks that an individual can perform. Thus, knowledge of these pathways may enable an individual to better predict the type of task that may be impaired with a certain restricted field of view. For example, for successful performance of activities or tasks involving ventral stream functioning, such as targeting and object recognition, a field of view as small as 40° may be sufficient. For successful performance of activities or tasks involving dorsal stream functioning, such as visual orientation to peripheral stimulation, controlling the position of a moving vehicle relative to the position of other vehicles (e.g., formation flying), or perceiving a full sense of immersion, a field of view much greater than 60° would likely be needed. Kruk and Runnings (1989), for example, stated that a field of view of 127° is required for flight simulation applications. However, a large field of view may create problems related to simulator sickness and/or postural instability. Moreover, achieving both a wide field of view and high resolution is difficult, given current technological limitations. The ideas discussed in this paper provide information to help establish the relative design priorities for different HMD applications. If accurate perception of self-motion is required, for example, it may be prudent to sacrifice display resolution to gain a greater field of view.

BINOCULAR INPUT

Under natural viewing conditions, the two eyes usually view a common region of visual space, albeit with horizontal binocular parallax (Howard & Rogers, 1995, 2002). However, with HMDs, the potential exists for the two eyes to receive very different input. When a monocular HMD is worn, for example, one eye views the HMD symbology while the other eye views a real-world scene, thus possibly creating interocular differences in brightness, contrast, color, flicker, shape, size, motion, and/or accommodative demand (Velger, 1998, p. 25). When a biocular or binocular HMD is worn, optical misalignment and/or image distortions between the two eyes' views can create such interocular differences as well.

Binocular Rivalry

In many cases, interocular differences in image characteristics can disrupt binocular vision by creating the conditions for binocular rivalry. *Binocular rivalry* (e.g., Blake, 1989; Breese, 1899; Howard, 2002; Howard & Rogers, 1995; Levelt, 1965) refers to a state of competition between the eyes, such that one eye inhibits the visual processing of the other eye. The visibility of the images in the two eyes fluctuates, with one eye's view becoming visible while the other eye's view is rendered invisible and suppressed, which reverses over time; the images projected to the two eyes are rarely visible simultaneously.

The inhibition evoked by binocular rivalry likely occurs at a number of levels throughout the visual system (Meng, Chen, & Qian, 2004), and it continues at a relatively constant rate during the course of suppression (Norman, Norman, & Bilotta, 2000). Binocular rivalry makes visual processing unstable and unpredictable. For example, Schall, Nawrot, Blake, and Yu (1993) showed that binocular rivalry suppression impairs the ability of observers to visually guide and direct attention to targets in the visual field.

This phenomenon of inattention and rivalry may be related to the phenomenon of inattentional blindness, wherein unexpected objects go unnoticed because attention is directed elsewhere (Mack & Rock, 1998; Mack, Tang, Tuma, Kahn, & Rock, 1992; Rock, Linnett, Grant, & Mack, 1992; Rock & Mack, 1994), or change blindness, wherein changes in objects go unnoticed because attention is directed elsewhere (e.g., Rensink, O'Regan, & Clark, 1995). These phenomena (see Palmer, 1999, pp. 534–540 for discussion) are important because they represent visual processes by which a person may miss information or signals while using an HMD.

Hakkinen (2003) stated that monocular HMDs produce a common problem of rivalry and perceptual instability and should be used only briefly (1–5 min). This claim, however, was made with regard to closed or occluded monocular HMDs, and it is not known whether rivalry would be such a problem with open or semitransparent monocular HMDs.

With respect to minimizing the occurrence of binocular rivalry when HMDs are worn, it may be that binocular fusion (i.e., sensory blending of the two eyes' views) can mitigate against rivalry. For example, with a semitransparent or open monocular HMD, the background scene would be viewed by both eyes, and binocular fusion of the background may mitigate against the binocular rivalry that could occur between the imagery in the eye that sees the HMD and the background scene viewed by the other eye. Blake and Boothroyd (1985) showed that when one eye views a set of vertical contours while the other eye simultaneously views a set of vertical contours (which should elicit binocular fusion) and a set of horizontal contours (which should provoke binocular rivalry), the result is binocular fusion, not rivalry. The presence of matching features in the two eyes seemed to make those features exempt from rivalry. Thus, it is possible that rivalry would not be a significant problem when monocular semitransparent HMDs are worn if the background scene viewed by both eyes is easily fusible. However, the results of one study suggest that even under conditions for which fusion is possible, binocular rivalry may still be a significant problem. Laramee and Ware (2002) found that response times were significantly greater on a table look-up task when the table was presented on a transparent monocular HMD (30% transmissive) while observers binocularly viewed dynamic background imagery presented on a television.

Even with interocular differences in image characteristics that can be binocularly fused, unwanted perceptual effects can still occur. For example, horizontal or vertical size disparities (i.e., size differences between the horizontal or vertical extent of corresponding images in the two eyes) can create the erroneous perception of a slanted surface in depth, which can perceptually interact with zero-disparity stimuli (Ogle, 1938; Pierce, Arrington, & Moreno, 1999; Pierce & Howard, 1997).

Partial Overlap HMDs

In some applications in which biocular or binocular HMDs are used, having a sufficient field of view is important for a sense of immersion. To increase the width of the field of view with biocular or binocular HMDs, such HMDs can be convergent or divergent partial overlap displays. Such displays have a central field of binocular overlap and peripheral side regions of monocular viewing (Velger, 1998, p. 56). Specifically, convergent displays have the right eye view the area to the left of the central region and the left eye view the area to the right of the central region. Divergent displays have the right eye view the area to the right of the central region and left eye view the area to the left of the central region.

The convergent and divergent partial overlap displays can produce perceptual conflicts such as *luning,* which refers to a subjective darkening of the monocular regions near the border with the binocular overlap region; it is possible that luning is related to binocular rivalry (Levelt, 1965; Velger, 1998, p. 56). Luning may interfere to some degree in tasks such as target detection. For example, Kruk and Longridge (1984) found that target detection was degraded within a 5° area near the binocular overlap regions for both a 25° overlap condition and a 45° degree overlap condition. Luning can be minimized by using a convergent display that has reduced luminance near the edges of the binocular region (Grigby & Tsou, 1994; Klymenko et al., 1994a, 1994b; Melzer & Moffitt, 1991; Rash, Mozo, McEntire & Licina, 1996; Velger, 1998, p. 56).

Luning may also be related to an interocular suppression that affects unpaired monocular images (called *half occlusions*), which do not normally occur in the real world (Nakayama & Shimojo, 1990). For example, with binocular viewing of a surface located behind an aperture (e.g., window), unpaired images will exist in one eye that do not exist in the other eye. These half occlusions will either undergo visual suppression or be perceived in a given depth location, depending upon whether the stimulus arrangement is consistent with the physics of occlusion. Luning may be a result of having unpaired images in one or both eyes that are inconsistent with the physics of occlusion.

In a study comparing HMDs with full binocular overlap to those with partial binocular overlap (convergent or divergent), Klymenko, Harding, Beasley, and Martin (1999) reported that response times were fastest, and accuracy highest, in a target acquisition task when HMDs with full binocular overlap were used; response times were slowest, and accuracy lowest, when HMDs with divergent partial overlap were employed; response times and accuracy were intermediate when HMDs with convergent partial overlap were used.

Tolerance Levels

Even with HMDs with full binocular overlap, the imagery projected to the two eyes should have the same or similar spatial characteristics; otherwise binocular rivalry may be provoked. With regard to visual tolerance for interocular differences in stimulation using a binocular HMD, Rash et al. (1996) suggested that the following interocular differences should be tolerable: a difference in luminance of up to 30%, a rotational difference of up to 10 arcmin, horizontal or vertical differences in image size of up to 1.5%, and deviation between centers of the two displays of 0.18 prism diopters. According to Tsou and Shenker (2000), the tolerance levels for misalignment errors for a closed binocular HMD are ±23 arcmin horizontal, ±11.5 arcmin vertical, and ±12 arcmin cyclorotational. For a semitransparent binocular HMD, the tolerance levels are ±10 arcmin horizontal, ±4 arcmin vertical, and ±6 arcmin cyclorotational.

With respect to interocular differences in luminance, Levelt (1965) reviewed the literature on binocular brightness summation as well as binocular rivalry. He reported that the luminance levels in the two eyes can usually be fused provided that the contrasts are not reversed and provided that the brightness differences are not too large. He suggested that the binocular combination process involves a relative weighting of the two eyes' input, with the presence of contours in a given eye increasing the weight of the coefficient for that eye.

Recommendations

The characteristics of binocular vision can affect the use of HMDs. For example, half occlusions may affect the viewing of partially overlapped HMDs. Moreover, the binocular fusion of an OTW scene may mitigate against the occurrence of binocular rivalry, which may involve suppression at different levels of the visual system. Thus, it is important to create viewing conditions that promote binocular fusion, which requires that the two eyes view the same or very similar images and scenes. With respect to semitransparent monocular HMDs, research should investigate whether binocular fusion of the background scene that is seen by both eyes mitigates against the rivalry that could occur between the imagery in the eye that sees the HMD and the background scene viewed by the other eye. With regard to biocular or binocular HMDs, the human visual system appears to be tolerant to interocular differences in luminance of no more than 30%, rotational differences of no more than 10 arcmin, horizontal or vertical differences in image size of no more than 1.5%, and deviation between centers of the two displays of no more than 0.18 prism diopters.

HEAD MOVEMENTS

Under natural viewing conditions, head movements create shifts or displacements in the position of retinal images. For example, if an observer voluntarily moves his or her head to the right (without an eye movement), objects that were positioned directly in front of the observer now appear located in the left visual hemifield, accompanied by a rightward shift (from the foveae) of the retinal images in the two eyes. With an HMD, head movements do not create shifts in the position of retinal images because the visual display moves with the head. In this case, if an observer wearing an HMD moves his or her head to the right, displayed objects that appeared to be located directly in front of the observer will continue to appear to be so located. To mimic natural viewing (i.e., employ conformal imagery), the displayed imagery could, in principle, be updated and shifted leftward on the visual display by computer, which, in turn, would shift the retinal images rightward. To do so, however, head position would need to be tracked.

In addition to voluntary head movements, involuntary head movements may also need to be tracked. Involuntary head movements occur when the HMD is used in an environment involving acceleration and/or vibration, a topic discussed at length by Velger (1998). In such an environment, involuntary head movements elicit reflexive eye movements called the *vestibulo-ocular reflex* (VOR). The VOR compensates for the involuntary head movements so that fixation is maintained on a given object and the image is stabilized on the retina. For instance, if an individual's head vibrates upward, the position of a given object would move downward relative to the eye and the retinal image would slip upward. In this case, the VOR would elicit a compensatory downward eye movement to maintain fixation on the object during the head movement. In the real world, such a compensatory eye movement system is important for maintaining fixation on objects during locomotion (Benson & Barnes, 1978; Velger, 1998, p. 207). When an HMD is worn, however, the VOR eye movements disrupt vision because, during the involuntary head movement produced by vibration, the retinal image moves with the head. With HMDs, the compensatory eye movements are inappropriate (Lee & King, 1971; Velger, 1998, pp. 208, 232).

Thus, it is not surprising that visual performance declines with head vibration. For example, visual acuity decreases, and errors in aiming increase, by as much as a factor of 10 during head vibration. The worst performance occurs at a frequency range of 3.2 to 5 Hz (Velger, 1998, p. 216; Wells & Griffin, 1987a, 1987b, 1988); below 1 Hz, smooth pursuit eye movements can compensate for the VOR (Huddleston, 1970; Velger, 1998, p. 216). One potential remedy for an inappropriate VOR response would be to measure the involuntary head movements with a head tracker and shift the image on the display in the same direction as the VOR (opposite the head movement), which would stabilize the retinal image (Velger, 1998, p. 225; Young, 1976). Draper et al. (1997) suggested that one cause of simulator sickness is the inability of the VOR to adapt to vestibular-visual mismatches.

Head Tracking

When an HMD is worn, the user's head position needs to be tracked for two reasons: to mimic natural viewing while making voluntary head movements and to maintain clear vision while working in an environment involving acceleration and/or vibration and, therefore, involuntary head movements. Yet head tracking is difficult, in part, because it can be relatively inaccurate owing to the amplitude and frequency of head movements (Velger, 1998, p. 224; Wells & Griffin, 1984, 1987a, b). For example, voluntary head movements may exceed angular velocities of several hundreds of degrees per second and accelerations of up to several thousand degrees per second squared (Wells & Haas, 1990). However, these values are at the extreme end of head movement velocities and accelerations; for example, Rash et al. (1998) found that 97% of all head movements of AH-64 pilots were between 0° and 120°/s. Based on these and other studies, several authors (Velger, 1998, pp. 227, 232; see also Ljung, Morf, & Falconer, 1978; Merhav & Velger, 1991) have recommended that head position computations be carried out at a rate of 120 to 240 Hz.

The temporal delay or lag between actual head position and update of the displayed imagery can seriously affect the use of HMDs (Keller & Colucci, 1998). Temporal delays or lags in the computation of head position, or in the update of the displayed imagery, can impair human performance and create disorientation, nausea, and discomfort (Grunwald & Kohn, 1994; So & Griffin, 1992; Velger, 1998, pp. 145, 171). This is attributable, in part, to a sensory conflict between proprioception and vision (Long & Wickens, 1994; So & Griffin, 1992; Velger, 1998, pp. 145, 171).

Despite the general agreement concerning the negative effects of temporal delay or lag in producing impaired performance and discomfort, there is little agreement as to the critical delay or lag beyond which impairment can be expected. According to So and Griffin (1992), the delay between head movement and imagery update needs to be less than 80 ms; according to Padmos and Milders (1992), the delay should be less than 40 ms; and according to Keller and Colucci (1998), the delay should be less than 16 ms.

Jagacinski and Flach (2003, p. 99) noted that phase lags set up a stability limit on the forward loop gain of a control system, with larger delays producing a decreasing range of gains that will yield stable control. With long delays, there may be no stable gain that produces a rapid head tracker response, and a proportional control system may not work.

To shorten the temporal delays or lags, one may need to increase the sampling rate or computation rate of head position, use a prediction algorithm to predict head position at some future point in time, or use auxiliary acceleration measurements (Merhav & Velger, 1991; Velger, 1998, p. 172). Olano, Cohen, Mine, and Bishop (1995) discussed techniques for combating latency by making the rendering latency equal one National Television Standards Committee field (16.7 ms) and by rendering the pixels in a scanned display based on position in the scan. Various types of head-tracking technology, including prediction algorithms and noise filtering, have been discussed by Melzer and Moffitt (1997) and by Velger (1998).

The lack of agreement in the literature regarding the critical delay beyond which impairment can be expected is troublesome. Part of the reason for the disagreement may be that different studies have measured different aspects of visual perception (recall the previous discussion of parvocellular versus magnocellular pathways), each of which may have possessed a different critical duration. What is needed are an understanding of what kind of visual events are occurring when a head movement is performed, voluntary or involuntary, and an updating of imagery within a short duration such that visual perception is undisturbed. The critical duration within which imagery must be updated may be a reflection of the time course of a kind of visual suppression called *head movement suppression.*

Head Movement Suppression

Head movement suppression is a kind of visual suppression that is likely to be elicited during head movements, especially voluntary head movements. This kind of visual suppression could serve to make visual perception stable and uninterrupted, despite the rapidly moving images that sweep across the retinae during a head movement, by suppressing the perception of unwanted image motion. Head movement suppression would be analogous to another form of visual suppression, called *saccadic suppression.* Because saccadic suppression has been studied for many years, many of its properties are well understood. Knowledge about saccadic suppression may inform research efforts on head movement suppression. For this reason we now briefly discuss the topic of saccadic suppression.

Saccadic suppression is the suppression of perception of image displacement and image motion during saccadic eye movements, which renders visual perception stable and uninterrupted despite the rapidly moving images that occur with the eye movements. Such suppressive effects are typically not noticeable because they are very brief, existing about 50 ms before the eye movement, extending throughout the eye movement, and terminating about 50 ms following the eye movement (Diamond, Ross, & Morrone, 2000). Saccadic suppression may be mediated at peripheral levels of visual processing (Roska, Nemeth, Orzo, & Werblin, 2000; Thilo, Santoro, Walsh, & Blakemore, 2004) as well as at cortical levels (Thiele, Henning, Kubischik, & Hoffmann, 2002) and affect both parvocellular and magnocellular pathways (Anand & Bridgeman, 2002; Burr, Morrone, & Ross, 2002). Saccadic suppression also may involve a distortion of visual space (Cho & Lee, 2003) and involve an extraretinal component (Diamond et al., 2000).

Turning now to head movement suppression, it remains to be determined whether the properties of such suppression are similar to those of saccadic suppression and what role head movement suppression may play in head tracking with HMDs. If head movement suppression occurs, and its duration is sufficiently long, then the shift in the displayed imagery on an HMD would go unnoticed even with a relatively long delay. However, if the duration of head movement suppression is relatively short, then the shift in displayed imagery would be noticed, which could create the conditions for unwanted image motion and perceptual instability or confusion (Velger, 1998; Wells & Haas, 1990). For the update of imagery to go unnoticed, its delay would need to be shorter than the duration of head movement suppression. Research should be performed to investigate the existence of head movement suppression, what kind of information (e.g., movement, color) gets suppressed, and for how long. This would allow one to predict the kind of perceptual confusion that might occur with different head-tracking lags.

Head-Tracking Accuracy

When an HMD with conformal imagery is used, it is important to measure head position with a high degree of accuracy (Martinsen, Havig, & Post, 2003). It is thought that an accuracy of 10 mrad is sufficient for launching air-to-air missiles, but approximately 2 mrad is needed for weapon aiming, similar to HUDs (Velger, 1998). Most systems can meet an accuracy of about 2 mrad near the line-of-sight direction, but accuracy is degraded to about 10 to 15 mrad at large eccentricities from the line-of-sight direction. Moreover, the head tracker should have a sampling rate of at least 120 Hz (Velger, 1998, p. 177).

During head movements, users typically move their eyes as well as their heads, such that the eye movement leads the head movement; there is an angular offset between eye orientation and head orientation (Robinson, Koth, & Ringenbach, 1976; Rolland, Ha, & Fidopiastis, 2004; Velger, 1998, p. 173). Thus, more accurate estimates of line of sight are available when both eye movements and head movements are measured (Velger, 1998, p. 173). However, it is difficult to measure eye movements accurately in the context of HMDs because many eye trackers are inaccurate, heavy, and bulky (Velger, 1998, pp. 174–175), and in many cases it may be difficult to mount inside the helmet the sensor needed to measure the eye movements.

Recommendations

A form of visual suppression called head movement suppression may exist and may set an upper limit on the acceptable lag or delay for display update when head-tracking systems are used. This suppression may be exploited to possibly control for the effects of a perceptual mismatch between vision and proprioception when head movements are performed with an HMD. The critical delay for display update is currently not known, but it may fall within the range of 16 to 80 ms. More research is needed to investigate the critical delay for display update. Head-tracking accuracy should be about 2 to 10 mrad, and the head tracker should sample at a rate of 120 Hz or higher.

SUMMARY

Based on our review of the literature, we make the following recommendations for the design and use of HMDs:

1. Perceptual constancy involves a cue integration process, which could affect the perceived size, depth, and/or distance within a scene presented on the HMD if any of the relevant cues are misregistered by the visual system. Thus, HMD brightness and contrast should be sufficient so as to minimize the tendency for accommodation to drift toward dark focus and vergence to drift toward dark vergence and, at the same time, produce a relatively large depth of focus. Representative minimum values would be a luminance level of at least 6.9 cd/m^2 and a Michelson contrast of at least .10. The tendency for accommodation to drift toward dark focus, and for vergence to drift toward dark vergence, may cause the size, depth, or speed of HMD symbology to be misperceived.

2. An accommodation-vergence mismatch can create several problems for the HMD user – namely, eyestrain or visual discomfort, blurred symbology, and misperception of distance, size, depth, or speed of objects presented on the HMD. The remedy for an accommodation-vergence mismatch is to maintain a steady convergence angle. More research is needed to determine the exact limits of tolerance for accommodation-vergence mismatches.

3. The functioning of the parvocellular and magnocellular pathways and the ventral and dorsal cortical streams determines, in part, the type of visual-motor tasks that an individual can perform, and knowledge of these pathways may enable one to better predict the type of task that may be impaired with a restricted field of view. Thus, for successful performance of activities such as targeting and object recognition, a field of view as small as 40° may be sufficient. For successful

performance of activities such as visual orientation to peripheral stimulation, controlling the position of a moving vehicle relative to the position of other vehicles (e.g., formation flying), or perceiving a full sense of immersion, a field of view much greater than 60° would likely be needed. Achieving both a wide field of view and high resolution is difficult; relative design priorities for a given HMD application need to be established.

4. The presence of mismatched binocular input may cause visual discomfort and disrupt viewing of an HMD. Such disruption can be minimized by creating conditions that promote binocular fusion. With semitransparent monocular HMDs, research should determine whether binocular fusion of the background scene that is seen by the two eyes mitigates against the rivalry that could occur between the imagery in the eye that sees the HMD and the background scene viewed by the other eye. This is important because binocular rivalry may involve suppression at different levels of the visual system. For biocular and binocular HMDs, representative tolerance levels are as follows: a difference in luminance of no more than 30%, a horizontal difference of no more than 10 to 23 arcmin, a vertical difference of no more than 4 to 11.5 arcmin, a rotational difference of no more than 6 to 12 arcmin, horizontal or vertical differences in image size of no more than 1.5%, and a deviation between centers of the two displays of no more than 0.18 prism diopters.

5. The possibility of the existence of head movement suppression may be exploited to control for the effects of a perceptual mismatch between vision and proprioception when head movements are performed with an HMD. This is important because temporal delays or lags between head movement and update of displayed imagery can impair human performance and create disorientation, nausea, and discomfort. The critical value of temporal delay beyond which vision becomes impaired is not consistent across the literature, ranging from 16 to 80 ms. Research should be performed to determine the critical delay and the role that head movement suppression may play in the use of HMDs.

In summary, new insights for potential design solutions for HMDs, such as those discussed in the present paper, may be gained by a thorough understanding of basic visual functioning. This is true even when a solution for a given problem is not immediately apparent; knowledge about basic visual functioning always has the potential of informing the development of a solution at a later point in time.

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